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WINTER THERMAL STRUCTURE, ICE CONDITIONS AND CLIMATE OF LAKE CH--ETC(U)
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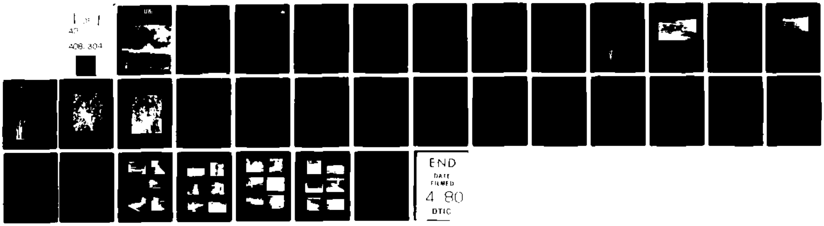

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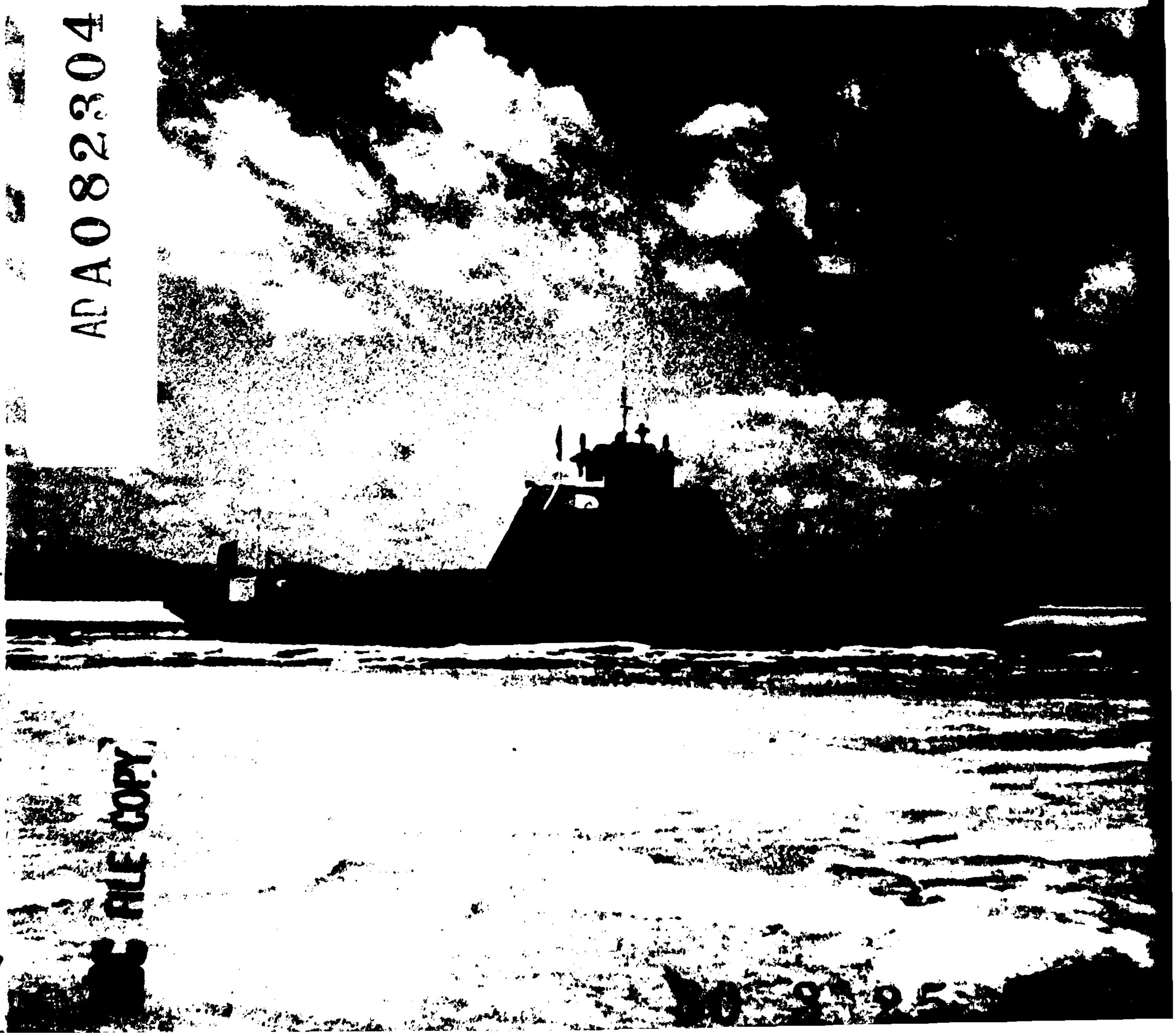
Winter thermal structure, ice conditions and climate of Lake Champlain



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Cover: Lake Champlain Transportation Co. ferry crossing Lake Champlain in land-fast ice cover. (Photograph by R. Bates.)

CRREL Report 80-2

Winter thermal structure, ice conditions and climate of Lake Champlain

Roy E. Bates

January 1980

Prepared for
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Winter thermal structure and ice conditions in the land-fast ice cover of Lake Champlain were studied in detail for the winters of 1975-76 and 1976-77. The lake was instrumented to a depth of 8.5 m with a string of highly calibrated thermistors attached to an ice mooring system and connected to a data logger at Shelburne Point, Vermont, during the winter of 1975-76 and at Gordon Landing on Grand Isle, Vermont, during 1976-77. This data logger automatically recorded water temperatures from the surface of the lake though snow, ice and water vertical profiles to the bottom of the lake every four hours. Pertinent meteorological parameters are presented for the appropriate measurement sites during the two winter periods, November '75–April '76, and November '76–April '77. Computations were made of freezing degree days (°C) for both winters and correlated with ice formation dates. Predictions of ice growth, using

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the Stefan equation with an empirical coefficient, were correlated with actual ice growth. Documentation was made of the Lake Champlain Transportation Company's first attempt at wintertime navigation by ferry from Gordon Landing, Vermont, to Cumberland Head, New York, in a land fast ice cover during one of the coldest winters of this century.

PREFACE

This report was prepared by Roy E. Bates, Meteorologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for the study described in this report was provided by Corps of Engineers Civil Works Project CWIS 31361, *Thermal Regimes as Disturbed by Man*. Dr. Anthony Gow, Darryl Calkins and Harold O'Brien of CRREL technically reviewed the manuscript of this report.

The Hanover Meteorological Detachment of the Maynard, Massachusetts, Meteorological Team, U.S. Army Atmospheric Sciences Laboratory, was invaluable to this study, furnishing meteorological instrumentation and manpower for field trips to Lake Champlain, Vermont, and extracting the recorded meteorological data.

Appreciation is also given to Mary-Lynn Brown for her data tabulation and analysis, Bryan Harrington for his assistance in assembly and installation of the electronic water temperature collection system, Dr. George Ashton for his helpful suggestions throughout the project and Dr. Y.C. Yen for reviewing the mathematical computations.

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WINTER THERMAL STRUCTURE, ICE CONDITIONS AND CLIMATE OF LAKE CHAMPLAIN

Roy E. Bates

INTRODUCTION

This is the second report on field measurements of *water temperature profiles and climate characterization* of the natural thermal environment of Lake Champlain. The first report (Bates 1976) describes the results of a study conducted during the winter of 1974-75 at a site near Shelburne Point on Lake Champlain, southwest of Burlington, Vermont. Included in the present report are data from the winter seasons of 1975-76 and 1976-77. The 1975-76 study was also conducted at the Shelburne Point site, but the measurement site was moved to the Lake Champlain Transportation Co. (LCT Co.) Ferry Dock at Gordon Landing, near Grand Isle, Vermont (Fig. 1) during the 1976-77 winter.

Meteorological measurements, ice temperatures and water temperatures were continuously recorded during the two winter periods. In both 1975-76 and 1976-77, ice thicknesses and ice surface conditions were observed and documented during each visit to the site, usually weekly. Two additional recording devices, not available during the 1974-75 winter, were installed: one to record wind speed and direction in the fall of 1975, and the other to record vertical and reflected shortwave radiation in the fall of 1976. These meteorological parameters are correlated with snow, ice and water temperature profiles throughout the two-year period. Measurements commenced each fall in late November and continued throughout the winter until the lake was ice-free each spring.

The CRREL site at the Gordon Landing, LCT Co. dock (Fig. 2) was ideally sited as it 1) provided a location for the instrumentation with access to power, 2) had a dock bubbler system that we could observe, and 3) gave us an opportunity to observe and conduct physical measurements during the LCT Co.'s first attempt at year-round navigation at their ferry crossing site on Lake Champlain.

OBJECTIVES

The main objectives of this study were the following:

1. To measure the heat transfer budget of a large temperate zone lake during ice formation, growth, and decay.

2. To further develop a catalog of wintertime water thermal profiles that characterize the natural thermal environment of water bodies such as lakes and reservoirs.

3. To gather complete meteorological data in order to modify or better understand predictive models for ice formation, growth, and decay of mid-latitude water bodies.

4. To observe the Lake Champlain wintertime ferry crossings in ice with a bubbler and flusher system installed at the Gordon Landing ferry slip and extending out in a loop from shore.

5. To further develop an offshore data collection system for placement in ice during extreme wintertime conditions.

CLIMATE

The long-term winter climate of the Burlington area was documented in Bates (1976). Table 1 of the present report gives long-term monthly normal temperatures (November - March) for Burlington International Airport in Burlington, Vermont. These long-term temperatures were determined to be representative of the Shelburne Point area. Consequently, the Burlington

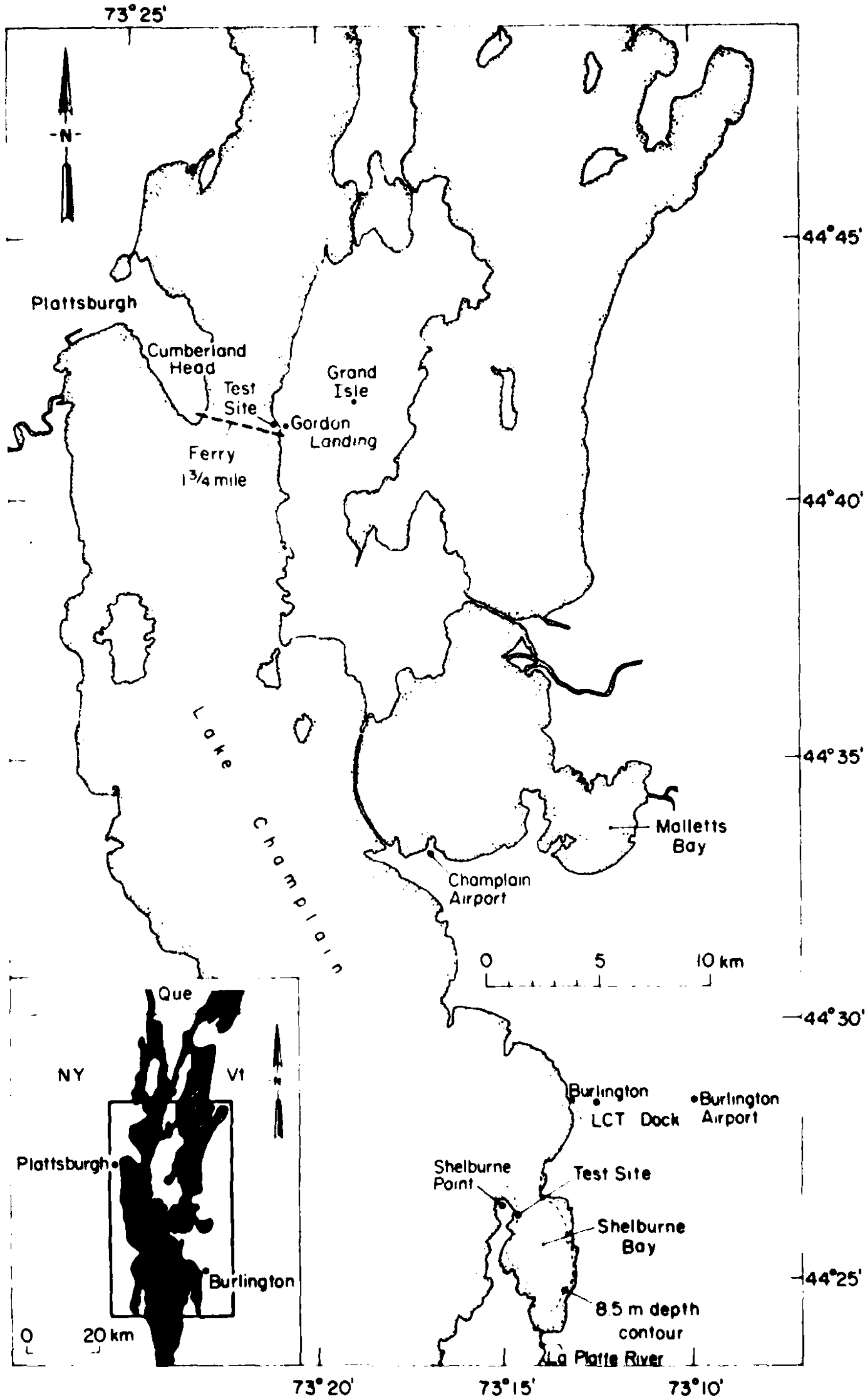


Figure 1. The Lake Champlain area, including Grand Isle and Shelburne test sites.

Figure 2. Lake Champlain Transportation Company ferry slip at Gordon Landing, Vermont.

Table 1. Comparison of Burlington Airport and Plattsburg AFB average long-term winter temperatures (°C).

	Normal Burlington, NWS	*(1975-76) Shelburne*	*Normal Plattsburg AFB*	*(1976-77) Gordon Landing*
November	2.8	–	3.1	–
December	-5.2	-6.4	-5.3	-6.8
January	-8.4	-8.7	-8.3	-11.9
February	-7.4	-0.3	-7.5	-6.2
March	-1.6	1.8	-1.7	1.9
April	6.1	–	5.8	–
Average for winter (December - March)	-5.6	-3.4	-5.7	-5.8
Mean annual	6.9		6.7	

long-term values will be used in this report for comparison with the measurements made in the winter of 1975-76 near Shelburne Point.

Average monthly air temperatures for the second winter of study 1976-77 are compared (Table 1) to the Plattsburg AFB, New York, 1976-77 winter and long-term normals. Plattsburg AFB is slightly inland but almost directly across the lake from the Gordon Landing location (see Fig. 1). Plattsburg AFB reports westerly prevailing wind directions averaging approximately 3 m/s during the winter months (U.S. Air Force Weather Service 1970). Strong wind gusts (to approximately

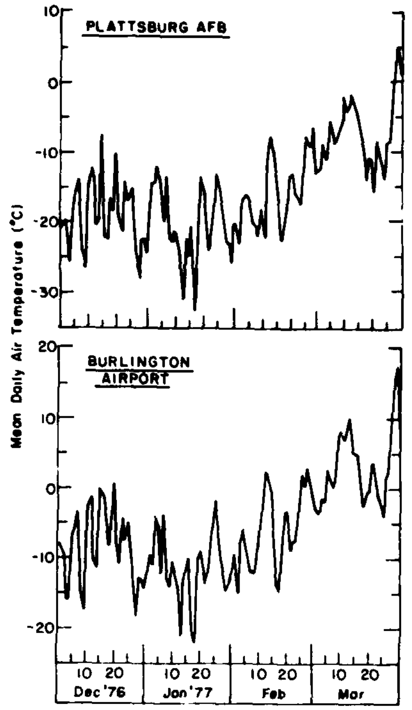


Figure 3. Average daily air temperatures (°C) for Plattsburg AFB and Burlington Airport. 1976-77 winter season.

20 m/s) were observed in the vicinity of the measurement site. Analysis of the long-term winter (December - March) temperatures for Plattsburg AFB (U.S. Air Force Weather Service 1970) shows that the wintertime temperature regime is quite similar to that of Burlington, with only a 0.1°C difference in the average winter temperatures (Table 1). The mean annual temperature for the two locations is 6.9°C for Burlington and 6.7°C for Plattsburg, for a difference of 0.2°C. This is reasonable as the major influence on climate at both cities is Lake Champlain. The lake, especially while unfrozen, has a large effect on the overall mesoclimate of nearby areas of New York and Vermont. The mean daily plots in Figure 3 for the winter of 1976-77 show that temperatures at Burlington airport and Plattsburg AFB for a single winter can be very similar. As the Plattsburg AFB long-term temperature record is for only 10 years, each winter season's data were compared to the 30-year normal record at Burlington airport (U.S. Department of Commerce 1973).

Table A3 gives the daily meteorological record observed during the winter season of 1975-76 at Shelburne Point and the record for the 1976-77 winter at Gordon Landing and Plattsburg AFB.

SITE PREPARATION AND DATA COLLECTION

Instrumentation, measurements and calibration

On 5 December 1975, meteorological recording instrumentation was installed for the second year in the CRREL heated instrumentation building at Shelburne Point, Vermont. A standard meteorological shelter containing a maximum and minimum thermometer and a hygrothermograph was again installed near the recorder building. An RO-2 continuous recording type wind instrument was installed at the measurement site for the first time. These instruments recorded hourly meteorological data throughout the winter of 1975-76. In addition, two Eppley pyrheliometers (one inverted over the ice) were installed at the Gordon Landing Ferry Dock (Fig. 4) during the winter of 1976-77 to measure vertical incoming and reflective shortwave radiation.

During the first week of December in both winters a string of thermistors and a Doric 30-channel data logger with a constant current source were installed. These thermistors were the same calibrated ones as used the previous winter and were installed at nearly the same water depth levels as described in Bates (1976). The temperature sensing instrumentation was designed to monitor the thermal profile from the bottom of the lake to the top of the data buoy extending (40 cm) above the water and/or ice surface. The data logger malfunctioned during December of 1975 and had to be returned to the factory. This necessitated obtaining water temperature measurements using thermocouples connected to a Fluke digital voltmeter throughout the winter.

Relocation of measurement site, Fall 1976

During early November 1976, CRREL personnel were invited to Burlington, Vermont, by the Lake Champlain Transportation Co. to discuss winter navigation problems that might be encountered during the company's first wintertime attempt to keep the Grand Isle Ferry open from Gordon Landing, Vermont, to Cumberland Head, New York (near Plattsburg). During discussions, CRREL was invited by the LCT Co. to move the study site from Shelburne Point, Vermont, to Grand Isle, Vermont, at the Gordon Landing ferry dock. In early December 1976, CRREL instrumentation was installed at Gordon Landing, as this site offered us an excellent opportunity to observe the first attempt of year-round navigation of Lake Champlain and to document the concurrent ice conditions, climate, and thermal influences nearby.

During the winter of 1976-77, the repaired data logger and a new calibrated 24-pair thermistor cable were installed at Gordon Landing. Table 2 gives the data logger

Figure 4. Gordon landing dock (solar radiation/wind site).

Table 2. Location of thermistors installed 100 m offshore from Gordon landing ferry dock.

Data logger channel	*Calibration thermistor*	*Location with respect to initial air/water interface*
2	1330	Top of ice buoy (40 cm above interface)
3	1331	Above surface installed in snow
4	1332	Above surface installed in snow-ice
5	1333	Initial air/water interface
6	1334	5 cm below interface
7	1335-1290*	10 cm below interface
8	1336-1288*	15 cm below interface
9	1337-1286*	20 cm below interface
10	1338-1189*	25 cm below interface
11	1339-1284*	30 cm below interface
12	1340-1188*	35 cm below interface
13	1341	40 cm below interface
14	1342	45 cm below interface
15	1343	50 cm below interface
16	1344	55 cm below interface
17	1345	75 cm below interface
18	1346	100 cm below interface
19	1347	150 cm below interface
20	1348	200 cm below interface
21	1349	400 cm below interface
22	1350	770 cm below interface
23	1351	800 cm below interface

*Thermistors replaced due to malfunction.

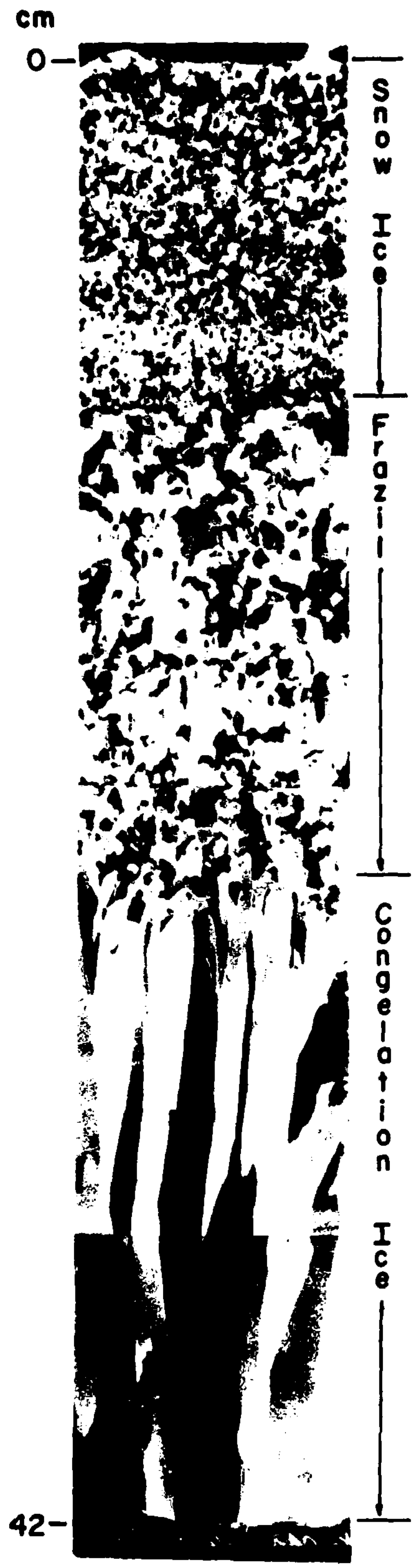


Figure 5. Crystal structure of Lake Champlain ice cover, Grand Isle, 3 March 1977.

channel numbers, thermistor serial numbers, and water depth relationships. Discussion on thermistor calibration, the water temperature data collection system, construction of the ice-free mooring, and the computer program through which the data were entered every four hours are all presented in Bates (1976). The temperature error for the water temperature thermistors was estimated to be ±0.16°C in the region around 0°C.

Visual observations, ice conditions, and pertinent photography.

Commencing in November 1975 at Shelburne Point and in December 1976 at Gordon Landing and continuing throughout the winter, a complete chronological account of visual ice observations and photographs was recorded. During 1975-76 a few ice measurements were made at St. Albans Bay, Vermont. These observations are all included in the Appendix A (Table A1 for 1975-76 and Table A2 for 1976-77).

During the period of 2-3 March 1977, ice samples were obtained at the Grand Isle site on 2 March 1977. These samples were taken to help determine the structure and type of ice that the Grand Isle Ferry was breaking while traversing the lake throughout the winter. In-situ beam tests of the flexural strength of the ice cover were performed at this time in conjunction with other ice property studies. A representative sample (Fig. 5) of the ice cover was subsequently examined for structural characteristics and found to be composed of 14 cm of frazil ice overlain by 9-10 cm of snow-ice and underlain by 18-19 cm of congelation ice. A full cross section of the structural characteristics of this ice cover is shown in Figure 5. Further description of the stratigraphic and structural fractures of the lake ice cover together with discussion of results of cantilever beam strength tests will be presented in a report by Gow (in prep.) covering two winters of ice strength analysis on Lake Champlain.

Photographs are shown of the Shelburne Shipyard's dock protection bubbler system in Figures A1, A2, and A5. This system performed extremely well during the winter of 1975-76. However, during the colder-than-normal January of 1977, ice formed earlier and growth was faster than the bubbler system could clear away. Consequently, ice had to be chopped away from the dock (see Fig. A17). A bubbler system installed at the LCT Co. ferry slip (Fig. A12) helped to keep the slip clear of ice and made it easier for the ferry boat to break free of the dock each morning.

Landsat imagery was obtained from the EROS Data Center (Sioux Falls, South Dakota) for the Lake Champlain area during the winter of 1976-77 to determine whether the open water area of the LCT Co.'s ferry crossing was discernible. Two pertinent photographs were received and enlargements made of the area under consideration for use in this report (Figs.

Figure 6. Landsat imagery of ice conditions on Lake Champlain on 9 March 1977.

Figure 7. Landsat imagery of ice conditions on Lake Champlain on 27 March 1977.

6 and 7). Figure 6 shows solid ice cover conditions on Lake Champlain on 9 March 1977 except for the ferry crossing area when the ice measured 38 cm at the Gordon Landing ferry installation. Figure 7 shows Lake Champlain ice conditions on 27 March 1977 at breakup of the main lake ice cover. The ferry crossing site is marked by an arrow in both photographs.

ANALYSIS

Air temperature comparisons

A continuous record of air temperature was maintained at Shelburne Point from December 1975 throughout March 1976 and at Gordon Landing from December 1976 through March 1977. Average daily and monthly air temperatures in degrees Celsius were determined for each winter.

Comparison of wintertime (December 1975 - March 1976) air temperature values for Shelburne Point with the long-term record (Table 1) and the winter data of 1974-75 shows the following:

1. The ice growth period during 1974-75 was previously established (Bates 1976) as a warmer than normal winter period.
2. During 1975-76, December and January were 1.2 and 0.3°C colder than normal, and February and March were 7.1 and 3.4°C warmer than normal, so that the winter season of 1975-76 averaged 2.2°C warmer than normal. However, this 2.2°C increase resulted from the warm February temperatures. Burlington airport recorded a temperature 3.3°C warmer than normal for February.
3. In comparing long-term normal values (Table 1) for Plattsburg AFB (closest station) to the 1976-77 season at Gordon Landing, it was found that temperatures at Gordon Landing were 1.6 and 3.2°C colder than normal in December and January, respectively.
4. February and March 1977 temperatures were 1.3 and 3.6°C warmer than normal. Thus, the overall winter season was near normal, i.e. ice growth period colder but ice decay period warmer.

Degree days of freezing

Accumulated freezing degree days (°C) for the winter of 1975-76 (Fig. 8) nearly approximate the long-term normal curve. Ice formed much earlier in 1975-76 than during the warmer winter of 1974-75 (Fig. 8) when freeze-over was late (on 4 February). First ice formed at the Shelburne site after 225 freezing degree days (°C) on 6 January and freeze-over was first observed after 300 freezing degree days on 16 January. Both values fell near the normal predicted ice formation date of 15 January for Lake Champlain (Bates et al. 1979).

An accumulated freezing degree day curve is plotted in Figure 9 for the 1976-77 season at Gordon Landing. First ice formed on 15 December after 186 freezing degree days. The curve for 1976-77 in Figure 9 for Grand Isle nearly approximates the curve for the same period at Burlington Airport. Shelburne Point reported freeze-over on 30 December (Fig. 9) after 270 freezing degree days (°C) at Burlington airport. The curves also show that colder-than-normal air temperatures prevailed at Burlington airport, 5 km inland from the lake, until ice formation. Then the two seasonal curves are similar for the rest of the ice growth period. Finally, both seasonal curves show much colder temperatures than normal during December and January, with the entire lake freezing over on 16 January after 450 freezing degree days (°C). This is the earliest freeze-over of the entire lake in this century.

Prediction of ice growth

Figure 10 is a plot of actual measured ice thickness for the winter of 1975-76 (see Table A1 for ice thicknesses) and computed ice growth. The growth curve, computed by the same method as used in Bates (1976) is determined by using the simplified Stefan equation:

$$t = \alpha(\Sigma\Delta T\theta)^{1/2}$$

where t is ice thickness, α is a correction factor, ΔT is air temperature below 0°C and θ is time. In the most simplified treatment of this equation, as described by Ashton (1978), the value of α is estimated as

$$\alpha = (2k_i/\rho_i\lambda)^{1/2}$$

where k_i is thermal conductivity, ρ_i is ice density and λ is latent heat of fusion. This expression equals 0.000121 m s$^{-1/2}$ °C$^{-1/2}$. This derivation assumes that the surface temperature T_s of the ice sheet is the same as the air temperature T_a. Since T_s differs from T_a for thin ice sheets (<0.2 m) in the initial growth period (Ashton 1978), an additional correction component (β) had to be included to achieve correlation between predicted and observed ice thicknesses. Thus, the equation for the correction coefficient α becomes:

$$\alpha = \beta\,(2\,k_i/\rho_i\,\lambda)^{1/2} = \beta\,(0.000121 \text{ m s}^{-1/2}\,{}^\circ\text{C}^{-1/2})$$

In Bates (1976) and from the above analysis, β was determined to equal 0.6 at both the Shelburne and

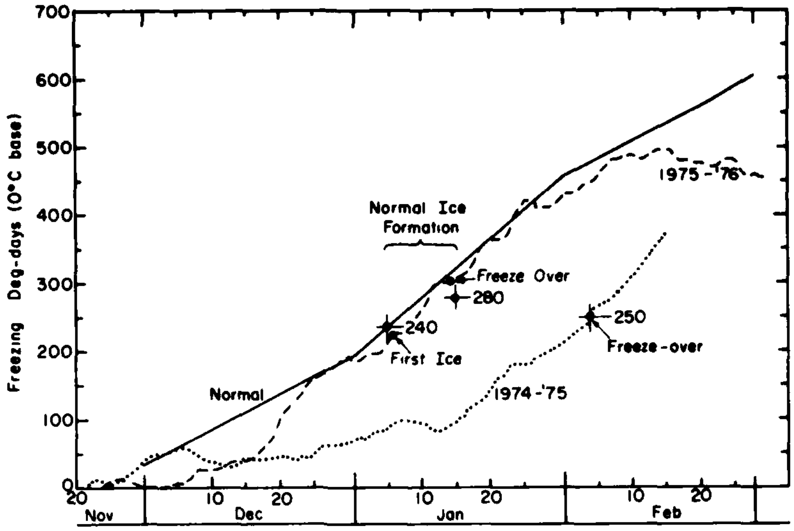


Figure 8. Accumulated degree days of freezing temperatures. 1974-75, 1975-76.

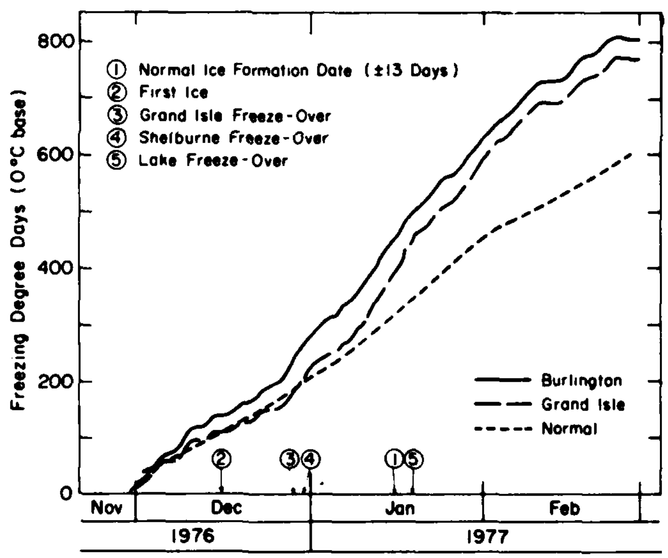


Figure 9. Accumulated degree-days of freezing temperatures. 1976-77.

Gordon Landing sites, giving a correction factor α of 0.00007 m $s^{-1/2}$ $°C^{-1/2}$. This coefficient falls within the bounds of typical empirical values of 0.00006 to 0.00010 m $s^{-1/2}$ $°C^{-1/2}$ obtained by investigators using this equation (Ashton 1978).

Utilizing 1975-76 winter data from Shelburne, the estimated ice growth curve is based on observed temperatures and an empirical correction coefficient of 0.00007 m $s^{-1/2}$ $°C^{-1/2}$, starting on 13 January 1976 (first permanent ice) (Fig. 10). The two curves show reasonable agreement; the predicted curve reaches a maximum thickness of 34 cm on 15 February and a maximum measured thickness of 36 cm occurs on 19 February. The two curves are compatible until 8 March when strong northerly winds broke up the ice at Shelburne Point.

The winter of 1976-77 is the first winter of observations at the Gordon Landing site. Figure 11 shows two ice growth curves determined from weekly measurements at the site. The in-shore ice was established a few days

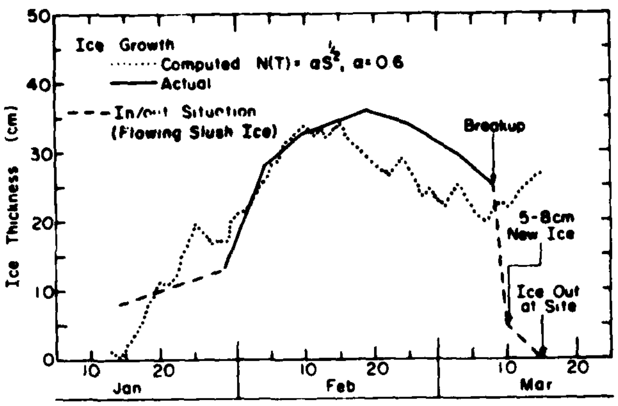


Figure 10. Ice growth curves (actual and computed) for Shelburne Point in 1976.

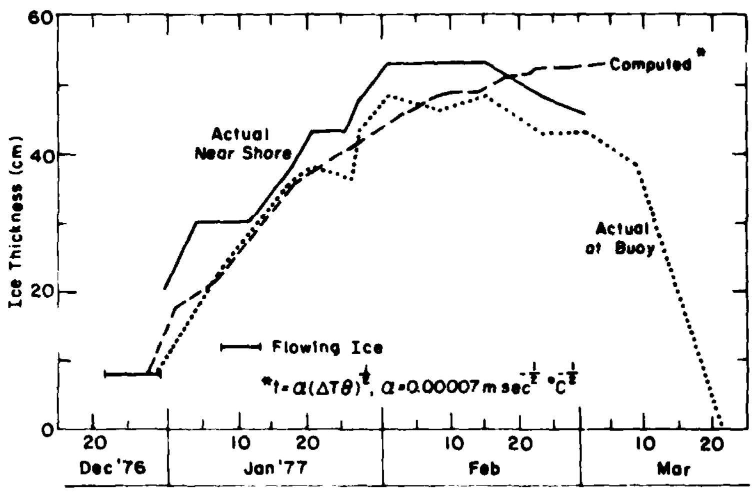


Figure 11. Ice growth curves (actual and computed) for Gordon Landing in 1977.

earlier and grew faster at the beginning of the ice season. The maximum thickness near shore measured 53 cm, while the ice maximum at the temperature profiling buoy measured 48 cm. The ice at the near-shore measurement site candled and melted out due to the influence of the bubbler system and ferry operations by 8 March. However, measurements continued through 15 March 1977 at the buoy site until melt-out at the buoy was recorded on 21 March 1977 (see Table A3 for complete descriptions of ice conditions for the area during the winter of 1976-77). The aerial Landsat photograph (Fig. 7) taken on 27 March shows ice breakup of the main lake and melt-out at the Gordon Landing site with a large open area (arrow) in the lake ice from ferry operations and increased solar radiation.

The estimated ice thickness prediction curve for 1976-77 using the Stefan equation and the correction factor of 0.00007 m $s^{-1/2}$ °C is also shown in Figure 11. Again, the predicted and actual ice growth curves demonstrate a high degree of correlation until the latter part of February when ice deterioration began.

Shelburne typically experiences a later freeze-over date than Gordon Landing, perhaps due to the difference in the geography of the two sites; i.e. the width of the lake at Shelburne Point is approximately 17 km as compared to 3.2 km at Gordon Landing. This wider part of the lake at Shelburne is prone to greater wind and wave disturbance, thus delaying land-fast ice formation. However, despite this difference in the initial date of

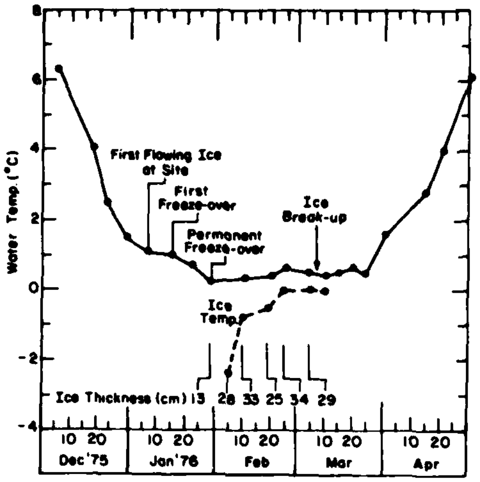


Figure 12. Ice thickness and related water and ice temperatures at Shelburne Point, Vermont.

ice formation, ice growth proceeded at a similar rate at both sites as demonstrated by the same computed empirical correction coefficient of 0.00007 m $s^{-1/2}$ $°C^{-1/2}$.

WATER AND ICE TEMPERATURE

As previously mentioned, measurements of water temperature at the Shelburne site during the 1975-76 winter season were made manually with a thermocouple string and a Fluke digital voltmeter. These profile measurements were made through the ice to a depth of approximately 1 m beneath the ice. Figure 12 is a weekly plot of both water and ice temperature for the winter of 1975-76 with ice thicknesses noted for each date. During periods of ice cover, the water temperature was measured as near as possible to the ice/water interface.

Figure 12 shows that water temperatures remained below 1°C from 15 January to 28 March 1976 and that the ice temperature was -2.4°C on 5 February, increasing to -0.8°C by 10 February and to 0°C by 25 February where it remained until breakup on 8 March 1976.

The water/ice temperature automatic profiling system was installed in early November 1976 at Gordon Landing and temperatures were accurately recorded at all depths listed in Table 3 during the 1976-77 winter period.

Figure 13 gives five water temperature/ice temperature profiles measured during the month of February 1977. These figures show both the profile nearest the time of measured ice thickness and the average profile for each selected date. Each date was selected to correspond with weekly ice thickness measurements. However, a profile could be drawn for any daily mean or four-hour period throughout the winter. Table 3 is an example of the computer printout of temperature for one day.

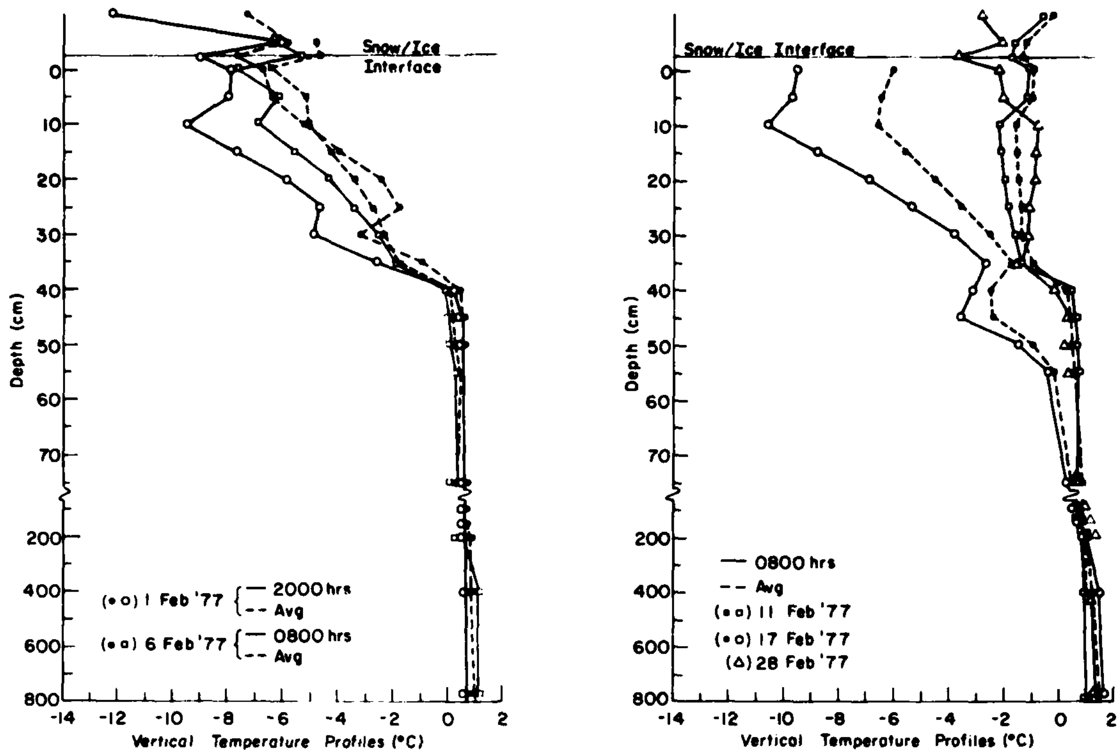
The 0°C point of water or ice on the five profiles (Fig. 13) does not necessarily correspond to the measured ice thickness because the thickness is measured weekly within 3 m of the buoy and not exactly where the buoy is frozen into the ice. However, it can be assumed that the approximate ice thickness of the buoy is at the 0°C point of the plotted profile, as this is generally at the ice/water interface. Further analysis shows that:

1. The lake bottom temperature was cooled to 0.7°C on 1 February. This bottom temperature warmed to 1.6°C by 28 February even though the ice thickness remained fairly constant throughout the month (43-48 cm, see Appendix Table A2). A possible explanation of this is the gain in net solar radiation received at the surface of a clear ice cover, with zero snow cover having less than 3 cm of snow-ice at this time of year, together with increased lake circulation.
2. Colder ice temperatures than air temperatures are measured in the ice cover both on a single profile and on the average plot for the day.
3. These colder ice temperatures can remain for a few hours or 24 to 48 hours depending on the surface (snow/ice) atmospheric heat exchange which is controlled by both mechanical and thermodynamic processes within the particular air mass over the site.

WIND

Summaries of 20-year average wind speed were compiled by Bates et al. (1979). These data, calculated from local climatological data at Burlington airport (U.S. Department of Commerce 1973), show that the wintertime (November - March) wind speeds average 4.1 m/s, prevailing from the south from November through February, with March reporting a northerly wind direction.

In analyzing the winter winds occurring at the two CRREL sites (shown in Table 2), it can be determined that average speeds of 2.2 and 2.9 m/s, respectively, were observed for the period of December through March. These values are approximately 2 and 1 m/s lower than the average speeds recorded at Burlington airport for similar winter periods and 1 m/s lower than those observed at Plattsburg AFB during 1976-77 (Table 2). This indicates that wind speeds recorded at the two CRREL sites may be somewhat lower than actual due to the slightly sheltered location of the sensors.



a. 1 and 6 February 1977. *b. 11, 17 and 28 February 1977.*

Figure 13. Water temperature/ice temperature profiles for February 1977. (Ice thickness varied between 43-48 cm during the month).

Table 3. Representative water temperature printout for Lake Champlain, 11 February 1977.

		Hour								
Chn	*Loc Depth*	*0*	*400*	*800*	*1200*	*1600*	*2000*	*Min*	*Max*	*Ave*
2	Air temp	-7.4	-3.0	-0.5	2.9	4.5	2.1	-7.4	4.5	-0.2
3	Snow	-2.8	-2.3	-1.6	-0.3	0.0	0.1	-2.8	0.1	-1.2
4	Snow/ice int	-3.3	-2.5	-1.7	-0.4	0.1	0.1	-3.3	0.1	-1.3
5	0	-3.9	-2.4	-1.0	0.4	1.0	0.6	-3.9	1.0	-0.9
6	5 cm	-3.1	-2.1	-1.1	0.1	0.3	0.2	-3.1	0.3	-1.0
7	10 cm	-3.3	-2.9	-2.1	-0.6	-0.2	-0.1	-3.3	-0.1	-1.5
8	15 cm	-2.8	-2.6	-2.1	-0.9	-0.5	-0.2	-2.8	-0.2	-1.5
9	20 cm	-2.2	-2.3	-1.9	-1.1	-0.6	-0.3	-2.3	-0.3	-1.4
10	25 cm	-1.8	-2.0	-1.8	-1.2	-0.7	-0.4	-2.0	-0.4	-1.3
11	30 cm	-1.4	-1.5	-1.5	-1.1	-0.7	-0.4	-1.5	-0.4	-1.1
12	35 cm	-1.1	-1.3	-1.3	-1.0	-0.6	-0.4	-1.3	-0.4	-0.9
13	40 cm	0.2	0.4	0.5	0.5	0.5	0.3	0.2	0.5	0.4
14	45 cm	0.4	0.5	0.6	0.6	0.6	0.5	0.4	0.6	0.5
15	50 cm	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
16	55 cm	0.7	0.7	0.7	0.7	0.6	0.7	0.6	0.7	0.7
17	75 cm	0.9	0.8	0.7	0.8	0.7	0.8	0.7	0.9	0.8
18	100 cm	0.9	0.9	0.8	0.9	0.8	0.8	0.8	0.9	0.8
19	150 cm	0.9	0.9	0.8	0.9	0.9	0.8	0.8	0.9	0.9
20	200 cm	0.9	1.0	0.8	1.0	1.0	0.9	0.8	1.0	0.9
21	400 cm	1.1	1.2	1.1	1.0	1.0	1.0	1.0	1.2	1.1
22	770 cm	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.1	1.0
23	800 cm	1.1	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.0

An analysis of wind speeds is given in Bates (1979) which indicates that speeds recorded at the Burlington airport appear to be more representative of overall Lake Champlain conditions.

Southeast and northwest winds prevailed at the Shelburne site during the winter of 1975-76, in contrast with the south-southwest winds at Burlington airport. During 1976-77, the Gordon Landing site recorded westerly winds as compared to those from the west-southwest at Plattsburg AFB. Maximum hourly wind speed for the 2 winter periods reached 17 m/s during 1975-76 and 16 m/s during 1976-77.

SOLAR RADIATION

Vertical incoming and reflected shortwave radiation data were recorded at Gordon Landing from December 1976 through March 1977. From these data it was determined that the total net shortwave radiation received averaged 79 langleys/day for February and 209 langleys/day during March (Table A3b). This increase in net solar radiation probably accounted for a portion of the total increase in water temperature during late February and March 1977. Further analysis of solar radiation effects on the thermal structure/heat budget, together with other sources of heat input (such as that released by bottom sediments, shoreline input, or within lake circulation), will be discussed after one or two more years of data have been analyzed.

GRAND ISLE FERRY OPERATIONS 1976-77

The Lake Champlain ferry crossings at Gordon Landing during the winter of 1976-77 are discussed and documented in Table A2. Weekly photographs of the open channel and ferry slip are also included in the Appendix. The photographs indicate the width of the open channel and amounts of broken ice contained in the channel and the ferry slip. The extremely cold temperatures during the fall and winter of 1976-77 cooled the surface water temperature of the lake to near 0°C by 25 December, which is approximately 20 days earlier than normal. The land-fast ice formed from Gordon Landing, Vt., to Cumberland Head, N.Y., on 28 December; thus, LCT Co.'s first attempt at winter navigation commenced on this date.

Lake Champlain completely froze over by 16 January 1977 which was the earliest date this century. Earlier dates of complete freeze-over were 7 January 1868 and 15 January 1893, as reported by the *Rutland Daily Herald* (1977). This shows the severity of the winter through January 1977. Throughout the winter of 1976-77, the *Rutland Daily Herald* and the *Burlington Free Press* had articles on the LCT Co. winter Grand Isle ferry operations. These articles are available in CRREL files for more detail on crossings in ice.

The first year's operation of the Grand Isle ferry throughout an entire winter season was successful, although some problems were encountered during breakup when wind caused ice floes to drift across the normal channel. However, the ferry was able to navigate around these floes and accomplish its crossing routine with only minor delays.

The bubbler system installed in the Gordon Landing slip was very efficient in keeping the slip ice free throughout the winter. Also, the ferry did not have to break itself free of overnight ice formations each morning when starting its daily schedule. Photographs of and notes on the bubbler efficiency are discussed in the Appendix.

CONCLUSIONS

After three winters of study, it is reasonably established that the Burlington airport long-term average temperatures and winds are representative of areas of Lake Champlain studied. The lake when unfrozen has a moderating influence on the climate of nearby areas of New York and Vermont. Thus, Plattsburg, New York, and Burlington, Vermont, experience similar climates as indicated by long-term climatic trends.

The winter of 1976-77 was much colder than the previous two winters studied at Shelburne. This is indicated by colder fall water temperatures, and by December and January air temperatures that averaged 1.6 and 3.2°C colder than normal, respectively. The date of 16 January 1977 is the earliest complete freeze-over of the lake in this century. Freeze-over was observed on 28 December 1976 after 186 freezing degree days (°C) at the Gordon Landing, Vermont, to Cumberland Head, New York, Grand Isle ferry crossing area. This is one of the earliest dates recorded for this area of the lake.

Freezing degree-days calculated for the two winters (1975-76 and 1976-77) at Shelburne show that freeze-over occurred at Shelburne Point after 300 and 270 freezing degree (°C) days, respectively. These data are compatible with the 250 freezing degree days (°C) calculated for the winter of 1974-75. The ice growth prediction curve at Shelburne for 1975-76 using the Stefan equation with an empirical coefficient of 0.6 compared favorably with the 0.5 value calculated for the 1974-75 winter. During 1976-77 an empirical

correction coefficient of 0.00007 m $s^{-½}$ $°C^{-½}$ was developed for the Grand Isle measurement site. Figure 11 shows the accuracy of using this correction coefficient for predicting ice growth when compared with the actual measured ice growth curve.

Analogies are given in the text between winds observed at CRREL sites at Shelburne Point and Grand Isle and long-term wind data analyzed for Plattsburg AFB and Burlington airport. The analysis showed that long-term winds for Burlington airport are fairly representative of conditions on the lake north of Burlington.

LCT Co.'s ferry operations throughout the cold winter of 1976-77 were a success, especially because Lake Champlain froze completely over on 16 January 1977, the earliest date this century. Documentation of these operations is discussed in the text and Appendix A. Landsat photos are presented which show the open water channel caused by ferry operations and document the exact breakup of Lake Champlain in March 1977.

RECOMMENDATIONS

Future work for additional research to remotely obtain meteorological and limnological data should include the following:

1. A lake thermal profile/heat budget model should be developed using 5 years of Lake Champlain data (available at the end of the 1978-79 winter season).
2. The performance of a new data collection buoy developed by CRREL and installed in Lake Champlain in October 1977 needs to be documented in detail.
3. A moored buoy which transmits by data collection platform to satellite and/or telemetry to shore should be installed or developed for research use in large lakes.
4. A mathematical model needs to be developed using the lake's complete thermal history and its relationship to light penetration.
5. Other types of water quality sensors should be developed and interfaced to shore-receiving stations for remotely determining turbidity, dissolved oxygen, etc.

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APPENDIX A: GENERAL OBSERVATIONS OF ICE CONDITIONS ON LAKE CHAMPLAIN
Winters of 1975-76 and 1976-77.

Table A1. Visual observations, measurements of ice conditions and pertinent photography, Shelburne Point, Vermont, 1975-1976 winter season.

18 Dec 75	LaPlatte River at southern end of Shelburne Bay is frozen over. Water temperature at site is 3.8°C.
23 Dec 75	Ice cover (black ice and slush ice) extends approximately 0.8 km from shore at St. Albans Bay site. Ice thickness estimated 8-10 cm thick. Brash ice and slush ice flowing in southern end of Shelburne Bay, solid ice extends approximately 100 m from shore. No ice at measurement site, water temperature is 2.5°C.
30 Dec 75	Ice extends approximately 0.5 km from shore at southern end of Shelburne Bay. Water temperature at measurement site is 1.5°C. Shore line at shipyard cluttered with brash ice which extends approximately 10 m.
6 Jan 76	Shoreline at shipyard cluttered with brash ice. Ice conditions at southern end of Shelburne Bay same as on 30 December. Water temperature is 1.1°C.
15 Jan 76	Ice formed overnight at shipyard site, 5-8 cm thick.
16 Jan 76	Ice at St. Albans Bay extends out as far as visible. Ice thickness averaged 38 cm (8–10 cm snow ice, 0-20 cm loose snow on top). Water temperature immediately below ice is 0.2°C. Uneven thin ice cover extends approximately 10 m out from shore at Shelburne Bay; water temperature is 1.0°C. Permanent ice cover extends out approximately half way between southern end of Shelburne Bay and shipyard site.
19 Jan 76	Shelburne Bay ice broke up from strong winds overnight.
22 Jan 76	Some floating brash ice at site. Ice has formed from south end of Shelburne Bay half way up to Shelburne Point. Water temperature is 0.7°C.
23 Jan 76	Freeze-over observed at measurement site.
27 Jan 76	Slight breakup at site overnight due to rain and strong winds.
28 Jan 76	Permanent freeze-over at Shelburne Point occurred with snowfall.

	Ice thickness		
	At buoy (cm)	*Near shore (cm)*	
29 Jan 76	13		8.5 cm snow ice, 4.5 cm clear or black ice. Water temperature below ice = 0.5°C, perhaps isothermal. Ice thickness southern end Shelburne Bay = 38 cm.
5 Feb 76	28		Ice temperature is -3.4°C. Ice on bay fractured and refrozen. Large 15-cm wide tidal crack 30 m offshore, 3 cm of new black ice formed in the crack area.
10 Feb 76	33		Ice temperature is -1.0°C, 15 cm of black ice formed between fractured blocks. Open water west of Shelburne Point in main lake, rest of lake frozen over.
19 Feb 76	25	36	Rafted ice 30 m offshore. Pressure ridges observed up to 60 cm in height 30 m beyond buoy. Ice thickness variable due to rafting. Surface of ice wet, water flows down drill holes. Ice temperature 8 cm beneath ice surface is -0.4°C, water temperature 50 cm beneath ice is 1.0°C. Shelburne Bay completely covered with ice, main lake west of Shelburne Point open. Figure A1 and A2 show the Shelburne shipyard bubbler system in operation. Figure A3 shows the buoy frozen in the ice for measuring the winter ice and water temperatures.
24 Feb 76	34	34	Maximum ice thickness for seasonal buoy. Black ice near buoy was 25 cm thick. Shelburne Bay is completely frozen over but lake to northwest of site is still open. Large rafted ice area 1 m high and oriented N/S still observed 30 m beyond buoy (see Fig. A4). Ice thickness measurements taken at St. Albans Bay showed 53 cm near the shore, 58 cm, 100 m out from shore and 56 cm, 300 m out from shore. Ice temperature 20 cm beneath ice surface is -0.2°C, 30 cm beneath ice surface is -0.1°C.
4 Mar 76	29	24	Ice at site smooth and covered with 8-10 cm of snow. Pressure ridge 27 m offshore, many small cracks in ice. Ice temperature at top is -0.2°C; halfway down drill hole is -0.2°C; and at ice/water interface 0°C. Took photo (Fig. A5) of bubbler system and ice conditions. In main body of water little wave action with floating chunks of ice.

Cont.	At buoy (cm)	Near shore (cm)	
	Ice thickness		
8 Mar 76			Ice broke up on 6 and 7 March with strong winds. Water level up considerably on lake. Ice blocks flowing in and out with wave action.
10 Mar 76	3-5		Windy at measurement site. Rafted ice 20-25 cm thick in some areas, ice unsafe. Southern end of Shelburne Bay ice cover estimated 20-35 cm thick. Thermistors read out manually at site. Ice temperatures throughout profile are −0.1 to −0.3°C. Water temperature beneath ice is 0°C. Ice in Shelburne Bay at site, western and northern side Shelburne Point free of ice.
15 Mar 76			Ice unsafe at measurement site. Water over ice. Open area extends out for approximately 800 m east, and to 100 beyond point extension south of site. Main lake open, windy and ice drifting with wave action. Southern end Shelburne Bay ice covered. Ice thickness at southern end averages 47 cm. Water temperature at site is 0.5°C. Ice temperature at southern end of bay is 0°C and isothermal. Figures A6 and A7 show instrument building and ice conditions.

18 Mar 76	Returned to Shelburne Point to service data logger. Snowfall helped reform ice in vicinity of data buoy. Ice is mostly unsafe frozen slush ice. Ice cracked with many ridges showing in the snow cover. Southern end of bay still frozen over.
24 Mar 76	Southern end of Shelburne Bay has 3 m of open water between shore and ice cover. Ice cover appears very thin and extends 1/3 of the way out into the bay. Lake level high. See photo (Fig. A8).
30 Mar 76	Lake level up to nearly highest level ever recorded, 100.6 ft above sea level, water within 3.5 cm of running to instrument building (see Fig. A9). Water in road at southern end of Shelburne Bay, some floating ice observed. Observations terminated for the 1975-76 winter season.
4 Apr 76	Lake level at 101.65 ft above sea level, highest ever recorded.
5 Apr 76	Lake level remains above normal. Three to four-foot swells on lake caused by southeast winds 20 mph, pounding instrument building at measurement site (see photo Fig. A10).

Table A2. Visual observations, measurements of ice conditions and pertinent photography, Grand Isle, Vermont, 1976-1977 winter season.

10 Nov 76	Instrument shelter and meteorological recorder building were moved from Shelburne Point, Vermont, to the Lake Champlain Transportation Co. (LTC) Ferry Dock at Gordon Landing, near Grand Isle, Vermont.
25 Nov 76	Visited new instrument site, installed instrument shelter at site.
9 Dec 76	Some brash ice in backwater at Gordon Landing Dock. All meteorological instruments and water temperature sensors installed for winter season (See Figure 3).
15 Dec 76	Some floating ice observed near breakwater, 3-9 cm thick.
22 Dec 76	Ice thickness 8-10 cm extending out approximately 0.8 km from shore.
27 Dec 76	Ice went out overnight, ice chunks floating in area.
28 Dec 76	Ice frozen completely across lake from Gordon Landing to Cumberland Point, 8-10 cm thick.

	At buoy (cm)	Near shore (cm)	
	Ice thickness		
28 Dec 76			First date ice frozen from shore to shore at Grand Isle, Vermont.
30 Dec 76	10	20	Temperature profile buoy frozen in rafted ice and not found due to snow cover on ice (see Fig. A11).
4 Jan 77	18	30	Snow (8 cm deep) on ice. Ferry channel across lake approximately three times the width of the ferry. Ice 20 cm thick near the edge of the boat channel, open water extends out approximately 60 m from boat slip area (Fig. A12). Bubbler system in operation.
12 Jan 77	28	30	Snow (13 cm deep) on ice. Snow-ice starting to form.
16 Jan 77			Lake Champlain completely frozen over (aircraft report). Earliest closing this century.

cont.	*At buoy (cm)*	*Near shore (cm)*	
18 Jan 77	36	38	Snow (8 cm deep) on ice. Snowing at site, visibility poor (Fig. A13).
21 Jan 77	38	43	Snow (15 cm deep) on ice. Rotated aluminum rod under the ice cover and found buoy. Removed ice around buoy and uprighted it to proper position (see Fig. A14). Figures A15 and A16 show ferry operation and ice at measurement site. Traveled to Shelburne Point (previous year's measurement site) and from discussions with the shipyard personnel, determined that freeze-over occurred on the night of 31 Dec. Ice thickness at Shelburne site measured 15 cm with 23 cm near shore. The shipyard's bubbler system became inoperable due to severe cold temperatures and the ice had to be chopped out around their main dock. (see Fig. A17).
26 Jan 77	36	43	Water temp.: 0°C.
28 Jan 77	43	48	
1 Feb 77	48	53	Snow (10 cm deep) on ice.
8 Feb 77	46	53	No ice growth around buoy in past week. Took photos of measurement buoy and ferry channel. (Fig. A18 and A19).
15 Feb 77	48	53	Maximum ice thickness observed at buoy site 48 cm, near shore 53 cm.
23 Feb 77	43	48	Most of flowing ice melted in ferry channel. Open ferry channel 30 m wider than on 8 Feb. (Fig. A20). Ice thickness on other areas of lake averaged 48 cm. Water temp. 2 m beneath ice averaged 0.8°C.
2 Mar 77	43	46	Ferry channel open 6-7 times width of ship. 30-40 m additional horizontal ice melt and buoy will be free of ice. (Fig. A21).
3 Mar 77			Ice strength tests made at site over a two-day period (Fig. A22). Water temperature profile taken to 40 m depth 1 km out on lake ice, ice thickness 41 cm, water temperature 1.3-1.5°C for entire profile. Ice thickness at Shelburne Point site is 33 cm. Lake complete frozen except around dock bubbler system (see Fig. A23).
9 Mar 77	38		Trouble with data logger system—water and ice temperature profiles were read manually.
10 Mar 77			Traversed Lake Champlain on ferry. Ice estimated 15-30 cm thick, with considerable candling taking place. Ice starting to break up along channel.
15 Mar 77	20		Considerable candling of ice. Ice unsafe.
21 Mar 77			Ice out at data buoy.
24 Mar 77			Took manual temperature profile and removed data logger for season. Open water at ferry channel approximately 0.5 km wide. Solid ice south of the Gordon Landing breakwater and north of the ferry channel indicates that the ice thawed out from the channel due to the ferry operations, radiation and wind effects. Photo taken of conditions at site. (Ice edge can be seen south in Fig. A24). Ice remains at Shelburne Point approximately 15 cm thick. Southern end Shelburne Bay open water.
31 Mar 77			Serviced meteorological instruments at site. Some floating ice pieces at site, no solid ice observed. Manual profile of water temperatures taken at site.
6 Apr 77			Water level of lake nearly up to instrument building. Took temperature profiles manually.
11 Apr 77			Removed all instrumentation for year except for 30-day air temperature recorder.
1 May 77			All data retrieval ended for 1976-1977 winter season.

Table A3. Climatological data for CRREL sites.
a. Shelburne Point, Vermont (1975-76).

Day	December Avg T (°C)	December Wind dir	December Wind speed	January Avg T (°C)	January Wind dir	January Wind speed	February Avg T (°C)	February Wind dir	February Wind speed	March Avg T (°C)	March Wind dir	March Wind speed
1	4.2			- 2.0	NW	2.2	- 0.6	–	–	3.0	NW	3.6
2	- 1.4			- 7.8	NW & TSE	2.7	- 5.6	–	–	- 7.5	WNW	1.0
3	- 2.2			- 0.3	SE	3.1	- 8.9	–	–	- 5.0	SE	2.2
4	- 7.5			- 5.3	vrb	1.3	- 2.5	–	–	3.1	SE	1.8
5	- 3.0*			-15.0	vrb	1.3	-12.2	–	–	10.8	SSE	5.8
6	0.2			-10.0	SE	3.6	- 9.2	vrb	1.0	6.4	SSE	1.3
7	-10.0			- 1.1	SE	3.6	- 8.3	vrb	1.3	0.6	SSE	2.2
8	- 8.6			- 8.8	NW	1.8	- 2.0	SE	4.0	- 4.4	–	1.0
9	- 1.4			-14.2	SE	2.7	- 4.2	calm	calm	- 2.8	–	1.8
10	2.2			-15.0	SE	1.8	- 0.6	SE	4.5	0.6	–	4.9
11	- 1.6			-19.1	calm	calm	4.8	NW	1.3	- 3.6	NW	2.7
12	- 7.2			-14.7	NW	1.0	- 3.4	NW & SE	2.2	- 8.6	–	2.7
13	- 5.6			- 4.8	SE	2.7	6.7	SE & NW	3.6	- 1.4	–	2.7
14	2.2			3.0	–	–	- 3.8	NW	1.3	- 3.4	NW	1.8
15	2.3			- 6.4	–	–	- 1.4	SE	5.4	- 1.2	NW & S	2.7
16	- 9.2			- 6.4	SE	3.1	8.0	vrb	1.3	- 7.7	NW	1.0
17	- 8.8			- 7.8	NW	1.8	3.9	SE & NW	1.8	- 7.0	WNW	1.3
18	- 9.8			-20.5	NW	1.3	2.2	SE	2.7	- 8.4	calm	calm
19	-18.9			-16.1	SE	2.2	5.0	SSE	3.1	- 1.4	SE	3.1
20	-19.7			- 4.5	SE	3.1	1.4	NW	1.3	13.4	SE	3.6
21	-14.4			0.3	ESE	1.0	2.0	SE	2.7	10.6	SSE	4.5
22	-10.9			- 2.2	S & NW	1.8	2.2	WNW	2.7	- 3.0	NW	1.3
23	-10.0	WNW	1.3	-23.1	vrb	1.3	- 8.7	NW	1.8	1.6	SE	3.1
24	-17.0	WNW	1.3	-20.1	calm	calm	- 1.9	SE	3.1	13.6	SE	4.9
25	-11.1	–	–	-13.9	calm	calm	6.6	calm	calm	12.8	SE	3.1
26	- 2.5	–	–	- 3.0	–	3.1	11.4	calm	calm	9.4	calm	calm
27	- 4.2	–	–	- 8.0	–	1.8	9.4	SSE & NW	1.3	16.2	SE	5.8
28	- 7.5	–	–	- 0.3	–	1.3	- 2.8	NW	1.3	10.0	SE & NW	1.3
29	- 9.4	–	–	0.0	SE	2.2	3.1	SE	3.6	6.4	NW	1.0
30	- 2.0	SE	4.9	- 8.1	NW	1.3					Site terminated	
31	- 5.0	SE & NW	1.3	-13.3	–	–					for year.	
Monthly avg.	- 6.4°C			- 8.7°C	SE & NW	1.9 (m/s)	- 0.3°C	SE & NW	2.1 (m/s)	1.8°C	NW & SE	2.5 (m/s) (avg 2.2 m/s)††

*: Data taken from Burlington Airport 1-5 December.

–: Missing due to recorder pen failure.

vrb: Variable.

††: Average speed Jan-Mar 1976.

b. Gordon Landing, Vermont, 1976-77.

	December				January				February				March				April			
Day	Avg temp (°C)	Wind dir	Wind speed (m/s)	Net rad (ly)	Avg temp (°C)	Wind dir	Wind speed (m/s)	Net rad (ly)	Avg temp (°C)	Wind dir	Wind speed (m/s)	Net rad (ly)	Avg temp (°C)	Wind dir	Wind speed (m/s)	Net rad (ly)	Avg temp (°C)	Wind dir	Wind speed (m/s)	Net rad (ly)
1	- 5.6				-12.5	WSW & SE	2.4	27	-11.9	SSW†	5.2†	30	- 3.3	*	*	147	2.8	WSW	6.5	518
2	- 7.8				- 5.3	vrb	1.3	76	-13.6	vrb	1.8	*	- 3.6	ENE†	4.0†	125	5.3	*	*	*
3	-13.9				- 6.7	E	1.8	23	- 8.3	NE	2.9	*	- 0.3	vrb	2.4	279	5.3	*	*	*
4	-10.0				- 3.9	WSW & SE	1.8	38	- 6.4	vrb	1.8	*	- 2.8	NNW	1.8	22	-0.3	*	*	*
5	- 3.9				- 5.8	WSW & NE	1.8	*	- 9.4	SW	2.7	*	2.5	N	2.7	94	2.5	*	*	94
6	- 3.6				-11.4	ENE	2.2	*	-13.9	SW	2.7	*	1.1	SE	2.7	60	0.0	ESE	3.8†	*
7	- 1.1				- 4.7	WSW & N	3.8	*	-10.6	S	2.2	*	0.6	vrb	1.1	95	-2.8	vrb	2.0	*
8	-12.2				-13.6	NE & NW	1.8	*	-10.8	vrb	2.2	140	1.1	S	1.8	180	-2.8	*	4.5	*
9	-15.3				-14.2	WNW	2.5	*	- 7.8	NE	2.7	53	5.8	ENE	2.5	304	-3.9	*	3.1	*
10	- 6.4				-12.8	SSW	3.4	*	- 7.8	vrb	1.8	48	8.1	vrb	1.1	184	1.1	*	1.8	*
11	- 1.7				-15.6	WSW	1.8	*	- 2.5	NE	2.7	20	4.7	vrb	0.4	351	Site terminated for year			
12	- 0.3				-14.7	NW*	1.8	*	1.4	vrb	0.6	16	6.7	vrb	1.3	292				
13	- 8.3				-18.3	vrb	0.9	*	1.4	vrb	1.5	20	7.2	vrb	0.9	64				
14	- 8.3	SSE	5.2		-13.1	NW & ENE	1.3	*	- 0.6	vrb*	3.1	61	4.7	SW	2.2	56				
15	2.8	SE & N	2.5		-14.7	WNW	1.8	*	- 6.7	vrb*	2.2	115	3.6	WSW	1.3	271				
16	- 1.4	NNW	1.8	133	-12.5	SW	2.0	*	-13.3	vrb*	2.5	136	1.9	E	1.5	66				
17	- 2.8	N	2.0	49	-23.1	vrb	1.1	*	-12.8	vrb	1.3	146	- 1.4	SSW	4.9	391				
18	- 7.2	WNW	5.4	*	-23.1	S	2.4	*	- 8.3	NE	2.9	147	- 4.4	SW	1.8	*				
19	- 7.5	SSE & N	2.2	*	-12.5	E & S	2.0	*	- 4.2	NE	2.2	*	- 2.8	SW	3.6	*				
20	0.3	vrb††	2.2	*	- 6.1	S	1.5	*	- 3.6	SSW	2.9	33	- 1.1	ENE	1.5	*				
21	- 6.7	WNW	6.0	*	- 7.2	NE & WSW	1.3	*	- 6.7	vrb	4.9	147	2.8	vrb	1.3	*				
22	- 9.2	WSW & SSE	8.0	*	-15.0	WSW	4.3	*	- 8.3	NE	3.1	65	1.4	W	1.1	*				
23	- 2.5	SSE	6.6	*	-12.5	NE	0.9	*	-11.1	SSW	3.1	87	- 2.2	W	4.2	*				
24	- 5.0	WSW	6.2	*	- 9.4	ENE	1.8	*	- 6.1	vrb	2.2	46	- 2.2	SSW	6.7	*				
25	- 3.3	SSE	6.6	*	- 3.6	ENE & SW	1.1	*	0.8	vrb	1.5	34	- 4.7	WSW	5.8	*				
26	- 3.3	SE & WNW	6.5	*	- 7.2	NE & SE	1.8	*	0.3	vrb	2.2	70	- 0.8	WNW	2.0	*				
27	-13.1	W	8.0	*	-11.7	ENE & E	4.5	*	1.7	NE & N††	3.6†	65	0.6	vrb	0.4	410				
28	-16.1	NNW & ENE	4.0	*	-12.8	NE	3.6	*	- 0.6	*	*	175	6.1	ENE	1.8	310				
29	-11.7	*	*	*	-15.8	ENE	4.9	*					11.1	ENE	2.0	262				
30	-10.3	WSW & N†	3.1†	*	-15.3	ENE†	3.4†	*					11.1	vrb	1.8	436				
31	-15.0	WSW	3.6	50	-12.8	*	*	*					6.7	S	2.9	*				
Monthly average	- 6.8	W	4.7	–	-11.9	W & NE	2.2	–	- 6.2	SW & NE	2.5	1654 (total for 21 days)	1.9	W	2.3	4399 (total for 21 days)			(2.9 m/s)**	

* = Data missing or not recorded.
† = More than ¼ of data missing.
** = Avg. speed, Dec. 1976-Mar. 1977.
†† = vrb = variable.

c. Plattsburg AFB, New York, 1976-1977.

November

Day	Avg temp (°C)	Wind dir	Wind speed (m/s)	Precipitation amt (cm)	Precipitation snow (cm)
1	0.0	NW	5.1		
2	0.0	W	3.1	0.05	
3	6.9	S	4.1	0.10	
4	3.6	vrb	1.0	1.09	
5	0.8	SSW	1.0		
6	1.7	SW	3.1		
7	1.9	NW	4.1		
8	- 3.1	NW	4.1		
9	- 5.6	SW	2.1		
10	- 0.6	ESE	1.0	0.02	
11	- 3.6	W	4.1		
12	- 3.9	WSW	1.5		
13	- 0.6	WSW	3.1		
14	9.4	WSW	3.1		
15	1.9	NW	1.0		
16	4.2	W	3.1		
17	4.2	SSW	3.1		
18	3.9	W	2.6		
19	5.8	W	5.7		
20	- 2.2	NW	4.6		
21	- 2.8	W	5.1		
22	- 1.1	NNW	4.1		
23	0.0	NW	3.1		
24	0.0	WSW	2.6		
25	- 1.1	ESE	1.0		
26	2.5	S	3.1	0.08	
27	11.4	S	4.1		
28	3.9	W	2.1	0.10	
29	- 3.6	WNW	2.1	0.51	2.50
30	- 7.8	SW	2.6		
31					
Monthly average or total	1.40°C	W	3.0	1.95 (total)	2.50 (total)

December

Day	Avg temp (°C)	Wind dir	Wind speed (m/s)	Precipitation amt (cm)	Precipitation snow (cm)
1	-10.6	SW	4.1		
2	- 9.7	SW	4.1		0.25
3	-16.1	W	3.1		
4	-12.5	S	1.5		0.51
5	- 6.9	W	1.0		
6	- 5.0	W	5.1		
7	- 3.6	W	6.2	0.71	
8	-14.7	N	2.6		
9	-17.2	NW	4.1		
10	- 5.3	SW	2.6		
11	- 2.2	NW	6.2		
12	- 3.3	N	1.0		
13	-10.8	SW	6.2		
14	-10.0	S	4.1		
15	2.2	SE	2.1		
16	- 2.8	N	0.5		
17	- 2.8	calm	0.0	0.08	2.03
18	- 6.9	SW	4.1	0.02	0.51
19	- 8.6	W	1.0		
20	- 0.3	W	2.1	0.13	
21	- 8.6	W	6.7		
22	-11.7	SW	3.1		
23	- 4.2	S	2.6		
24	- 7.2	W	4.1		
25	- 6.1	S	2.6		
26	- 4.7	WNW	1.0	0.20	3.30
27	-14.4	W	4.1		
28	-18.6	NNW	2.1	0.02	
29	-12.5	N	2.1	0.02	3.05
30	-12.5	W	4.1		
31	-14.2	W	5.1		
Monthly average or total	- 8.4	WSW	3.2	1.18	9.65

January

Day	Avg temp (°C)	Wind dir	Wind speed (m/s)	Precipitation amt (cm)	Precipitation snow (cm)
1	-11.1	W	6.2	0.05	1.78
2	- 4.4	W	2.6		
3	- 4.4	vrb	2.1	0.02	0.76
4	- 2.5	SW	2.1	0.10	1.52
5	- 5.3	N	2.1		
6	-10.3	SSW	4.1		
7	- 3.9	SW	4.1	0.23	2.54
8	-12.5	S	3.1		
9	-13.3	vrb	3.1		
10	-11.4	N	3.1	2.11	25.40
11	-13.3	W	5.1	0.02	2.54
12	-15.0	W	2.1		
13	-21.1	W	1.0	0.02	1.27
14	-12.8	N	1.0	0.05	2.79
15	-15.3	calm	0.0		
16	-11.1	W	3.1		
17	-23.1	W	3.1		
18	-21.4	W	3.1		
19	- 8.9	SW	3.1		
20	- 3.9	W	4.1	0.05	
21	- 8.1	W	3.1		
22	-14.4	NW	5.1		
23	-11.7	vrb	2.1		
24	- 7.8	WSW	2.1		
25	- 3.1	S	1.0	0.33	7.11
26	- 5.6	vrb	2.1	0.05	4.83
27	-10.3	SW	6.2		
28	-13.3	vrb	5.7		
29	-13.3	SW	6.2		
30	-16.4	SW	5.1		
31	-10.8	SW	7.7		
Monthly average or total	-11.0	W	3.4	3.03	50.54

February

Day	Avg temp (°C)	Wind dir	Wind speed (m/s)	Precipitation amt (cm)	Precipitation snow (cm)
1	-10.3	W	5.1		
2	-13.6	NW	3.1		
3	- 7.2	S	4.1	0.02	0.76
4	- 6.1	W	2.6		
5	- 8.3	N	3.1	0.05	0.51
6	-10.6	W	4.1		
7	-10.6	NW	2.6	0.05	0.76
8	-12.2	SW	3.6		
9	- 8.1	S	2.1		
10	-12.2	WNW	3.1	0.05	3.56
11	- 2.2	SW	4.1		
12	2.2	vrb	1.0		
13	1.9	SSE	4.1	0.02	
14	- 0.3	SW	6.2		
15	- 5.8	W	4.6		
16	-12.8	vrb	4.1		
17	-12.2	W	3.1		
18	- 9.4	S	4.1		
19	- 3.6	S	3.1	0.05	2.03
20	- 3.1	N	4.1	0.18	2.54
21	- 6.1	WNW	6.7	0.02	0.25
22	- 6.9	S	4.1		0.51
23	- 8.1	N	3.1		0.25
24	- 4.2	SSE	9.3	0.08	
25	1.7	SW	2.1	2.97	14.73
26	0.6	W	4.1		
27	3.1	S	7.2		
28	0.3	W	5.7		
29					
30					
31					
Monthly average or total	- 5.9°C	SW	4.1	3.49	25.90

March

Day	Avg temp (°C)	Wind dir	Wind speed (m/s)	Precipitation amt (cm)	Precipitation snow (cm)
1	- 3.1	W	4.1	0.05	3.56
2	- 2.5	WSW	5.1		
3	1.1	WNW	4.1		
4	- 1.4	SSE	4.6	1.14	11.43
5	4.4	SSW	3.6	0.05	
6	2.8	W	4.1		
7	1.1	W	2.1		
8	2.5	WSW	3.1		
9	4.2	SSE	4.1		
10	7.8	S	2.1		
11	5.8	vrb	1.0		
12	6.7	SSE	3.1		
13	8.3	SE	4.1	1.35	
14	6.4	N	3.6	0.89	
15	5.0	vrb	3.6		
16	2.8	SE	3.1	0.53	
17	0.0	WNW	6.2		
18	- 4.2	N	4.1		
19	- 0.8	NW	5.1		
20	- 1.1	S	4.1		
21	- 3.3	W	2.6	0.08	1.27
22	1.4	N	4.1	0.96	5.08
23	0.0	N	6.7	2.16	11.40
24	- 1.7	NW	6.2		
25	- 4.4	NW	6.2		
26	1.1	N	3.1		
27	1.1	vrb	1.0		
28	6.7	SSE	3.1	0.20	
29	10.8	SSE	5.1	0.43	
30	15.0	SW	4.1	0.33	
31	8.9	SSE	4.1	0.41	
Monthly average or total	2.6°C	W & SSE	3.9	8.58	32.74

Figure A1. 19 February 1976.

Figure A2. 19 February 1976.

Figure A3. 19 February 1976.

Figure A4. 24 February 1976.

Figure A5. 4 March 1976.

Figure A6. 15 March 1976.

Figure A7. 15 March 1976.

Figure A8. 24 March 1976.

Figure A9. 30 March 1976.

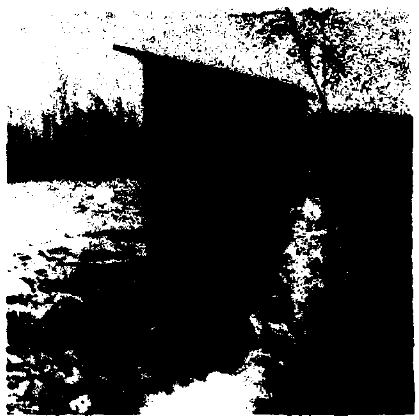

Figure A10. 5 May 1976.

Figure A11. 30 December 1976.

Figure A12. 4 January 1977.

Figure A13. 18 January 1977.

Figure A14. 21 January 1977.

Figure A15. 21 January 1977.

Figure A16. 21 January 1977.

Figure A17. 21 January 1977.

Figure A18. 8 February 1977.

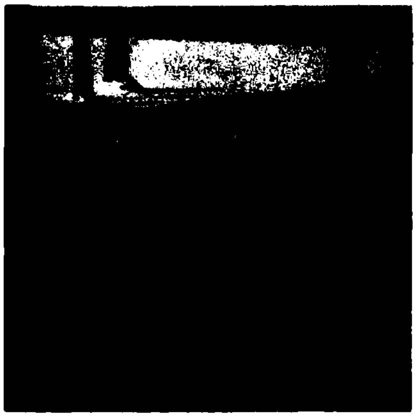

Figure A19. 8 February 1977.

Figure A20. 23 February 1977.

Figure A21. 2 March 1977.

Figure A22. 3 March 1977.

Figure A23. 3 March 1977.

Figure A24. 24 March 1977.

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